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MINIATURE PROPULSION COMPONENTS FOR THE PLUTO FAST FLYBY SPACECRAFT

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Abstract

Pluto is the only planet in our solar system not yet visited by our spacecraft. Recent observations through the Hubble Space Telescope have *given* us a glimpse of Pluto and it's moon Charm-t, but their small size and immense distance from earth have preserved their mystery. A novel Pluto spacecraft is being designed to meet the challenge facing planetary missions today: be smaller, be lighter and be less expensive. In fact the preliminary design calls for • vehicle that is less than one-quarter the size of the Voyager Spacecraft.

Drawing upon miniature valve technology developed for various Strategic Defense Initiative (SDI) programs, Moog has developed three miniature components for this very small 110-164 kilogram (includes propellant) spacecraft: cold gas thruster (7.S g), latch valve (60 g) and regulator (300 g). Design details and performance data are presented for each component.

Introduction

The Jet Propulsion Laboratory (JPL) is the team leader of a NASA program to develop a reconnaissance mission to Pluto and it's moon Charon.

As currently envisioned the mission will consist d two spacecraft launched on separate vehicles in 2000/2001 on direct trajectories to pass within -15,000 km of Pluto and Charon in 2008/2011. Scientific data will be obtained during the flyby and then transmitted to earth after the encounter.

Two very small spacecraft are being designed to perform this first exploration of our outermost planet. Existing plans have each spacecraft configured with four scientific instruments designed to obtain data on both hemispheres of Pluto and Charon in the form of visual images, infrared and ultraviolet data and radio science. The goal of the mission is to deliver two 100 kg elms spacecraft costing less than $400 million for both, on direct trajectories to the Pluto-Charon system taking approximately 7-10 years. A direct trajectory will allow the spacecraft to arrive before the collapse of Pluto's atmosphere. Pluto's orbit around the sun reached it's 29.7 AU perihelion in 1989 and is currently traveling towards it's 49.S AU aphelion which should occur in 2113. As a result , it's atmosphere, which is believed to exist for only about the warmest few decades around perihelion, will begin to condense onto the surface of Pluto, thus ending the opportunity for scientific study of Pluto's atmosphere for another ~200 years.[1] The requirement for a less than 10 year cruise places a premium on low spacecraft mass.

Initial design studies produced a spacecraft mass of 165 kg with propellant. NASA'S Office of Advanced Concepts and Technology is funding research and demonstration of new technologies that will benefit the Pluto mission. Under a program called Advanced Technology Insertion NASA has funded proof-of-concept hardware development to enable the Pluto Fast Flyby spacecraft to be reduced to 100 kg. It is under this activity that Moog has developed and demonstrated miniature propulsion components.

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Propulsion System Components

The baseline propulsion system includes a set of monopropellant hydrazine thrusters for trajectory (Delta V) corrections and a bank of cold gas thrusters for three-axis stabilization. The propulsion system is a hybrid blow-down design which utilizes a portion of tbe hydrazine tank pressurant gas as the working fluid for the cold gas attitude control thrusters. Figure 1 shows the location of the thrusters on the spacecraft and Figure 2 is a schematic of the propulsion system.

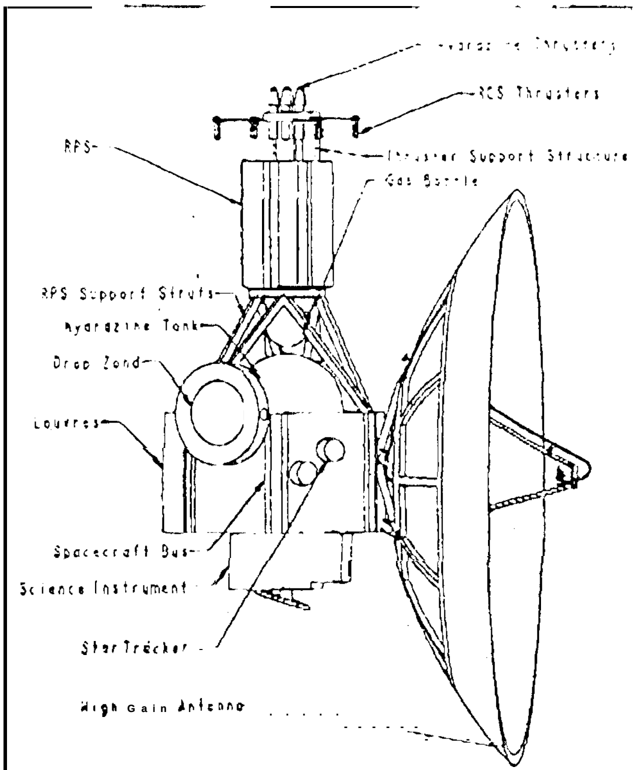

Figure 1 Pluto Spacecraft Configuration

Redundancy is provided through the use of multiple thruster branches and latching isolation valves. Each branch of delta-V thrusters consist of three 4,4 N (1 lbf) thrusters which also provide the thrust vector control function when the firing sequence and duration arc controlled. The hydrazine tank will be repressurized as required throughout the mission. Each attitude control thruster branch has eight 0.0045 N (0.001 lbf) thrusters. Cold gas thrusters were selected for this mission because they satisfy the thrust level, response time and minimum impulse bit requirements in addition to minimizing potential spacecraft impingement problems. The delta-V thrusters will utilize redundant thruster valves and

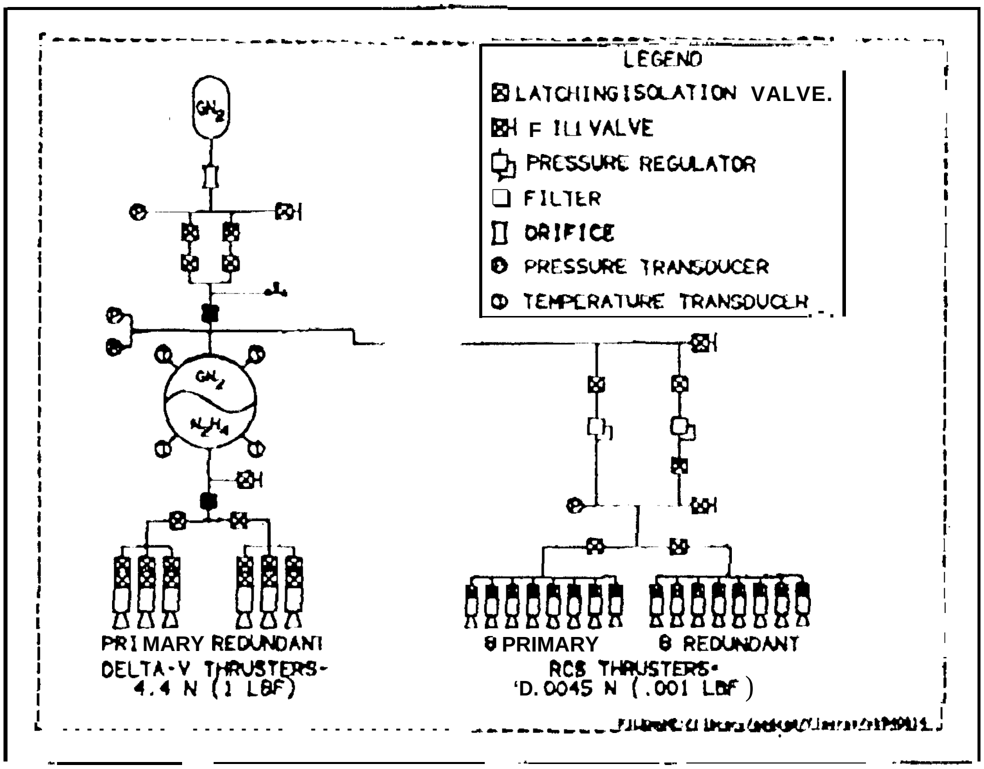

Figure 2 Propulsion System Schematic

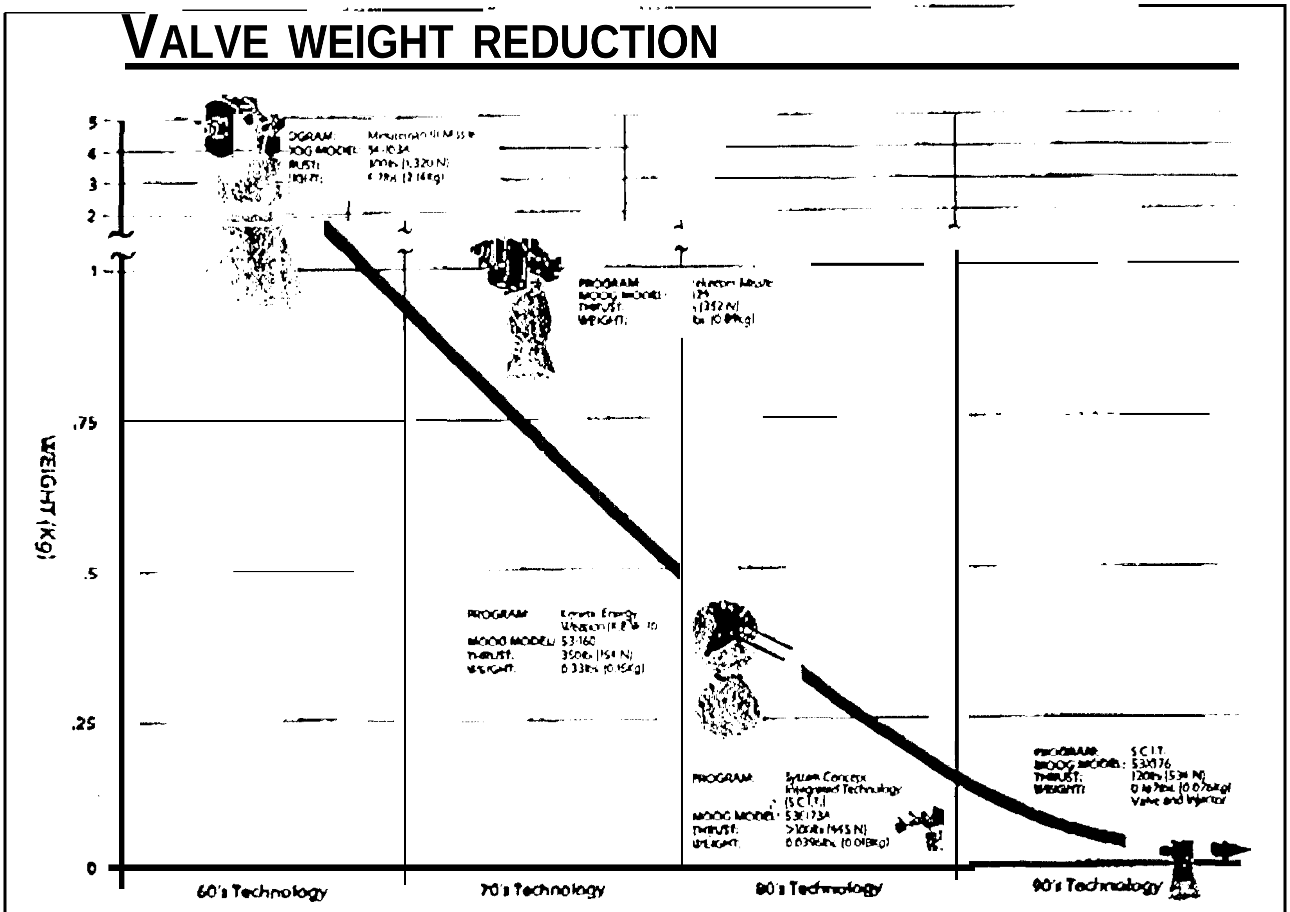

Figure 3 **Hardware Size Reduction**

the cold gas thrusters will have single valves. **Dual** valves **are also being** considered for the cold **gas thrusters,**

Over the past several **years** Moog **has** made **significant strides** in **reducing the size and mass of** propulsion **components** in **response** to **several Strategic** Defense Initiative **Programs.** An example of current **gains in** i-educing hardware **size** is given in **Figure 3.** A combination of **good** engineering **practices** and **technology** advances **over the** years **has** snowed us to **achieve significant** reductions ***in envelope and mass. We were*** abk to 'apply **the lessons** learnt **during** tbe **SDI programs** to **the needs *of the Pluto*** Fast ***Flyby*** program.

<u>Cold Gas Thruster</u>

The primary objectives of **the Advanced Technology Insertion** Program **were reductions in mass, gas leakage** ● nd power **consumption. These parameters are especially** important in **light** of the multiple

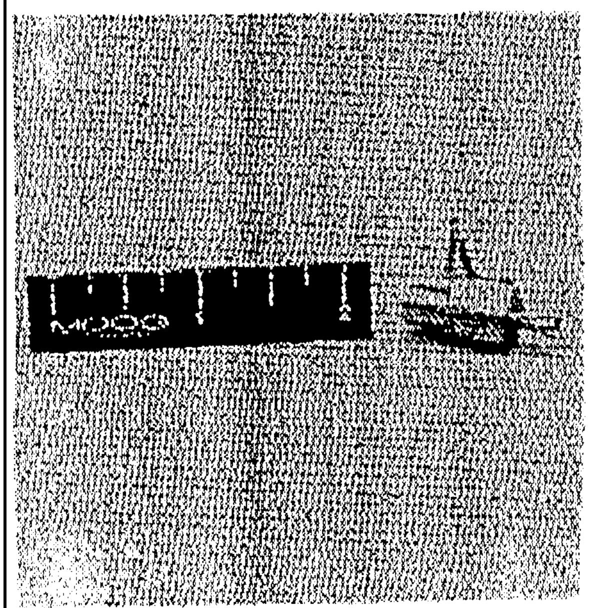

Figure 4 Cold Gas Thruster

thrusters utilized due to the redundancy requirements. The cold gas thruster, see Figure 4, consists of a normally closed sliding fit solenoid with a simple conical diverging nozzle. As shown in Figure 5 the solenoid has all welded construction to minimize external leakage.

A helical spring provides the closing force on the armature into which a PTFE Teflon seal is swaged. The valve seat is integral with the valve body/nozzle assembly. The coil is wound and potted on a plastic bobbin to provide high reliability performance when exposed to spacecraft operational environments. The coil as well as the outer polepiece are installed from the nozzle end of the thruster. Both parts are attached to the valve body with a spring clip. A 10 micron filter is used to protect the valve from contamination in the propellant gas.

Thrust Output

The Pluto Fast Flyby thruster sizing was based on experience gained with numerous other thrusters built and tested by Moog. Moog does not have a sensitive enough thrust stand to accurately measure 0.0045N (0.001 lbf) force level and the following method was utilized to calculate the necessary seat and throat size.

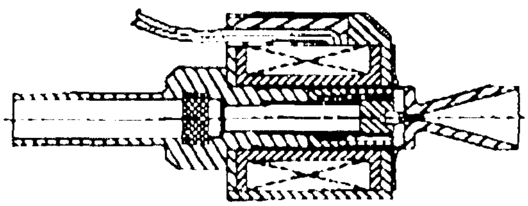

Figure 5 Cold Gas Thruster Cross Section

$$F = F^* P_1 A_{eq}$$

where:

F = Thrust (N)
F^* = Thrust Coefficient (non-dimensional)
P_1 = Inlet Pressure (MPa)
A_{eq} = Equivalent Flow Area (mm^2)

The theoretical best value of the thrust coefficient is 1.9. Prior experience has produced thrust coefficients in the range of 1.2 to 1.4. A thrust coefficient value of 1.3 was used for all sizing calculations.

The thrust output was calculated according to the following equation:

Table 1. Cold Gas Thruster Characteristics

Characteristic	Requirement	Demonstrated Value
Operating Fluids	GN_2, Hydrazine Vapors	GN_2
Weight	≤ 20 g (0.044 lbs)	7.34 g (0.016 lbs)
Thrust	0.0045N (0.001 lbf) @ 34.5 kPa (5psi) inlet pressure in vacuum	0.0045N @ 34.5 kPa inlet pressure in vacuum (calculated)
Minimum Impulse Bit	≤ 1 x 10^{-4} N-s	≤ 1 x 10^{-4} N-s
Operating Pressure	34.5 kPa (5 psi)	34.5 kPa
Proof Pressure	2.07 MPa (300 psi)	2.07 MPa
Burst Pressure	≥ 3.5 MPa (500 psi)	3.5 MPa
Voltage - Operating	24 to 32 Vdc	24 to 32 Vdc
Pull -In	≤20 Vdc @ 34.5 kPa (5 psi), 45°C	13 Vdc @ 34.5 kPa, 25°C (77°F)
Response Time (open/close)	≤2.5 ms @ 24 Vdc, 34.5 kPa, (5 psi) 45°C (113°F)	Open - 0.94 ms @ 25°C Close - 0.2 ms @ 25°C
Leakage - Internal	≤0.01 scc/m @ 34.5kPa (5 psi)	1.04 x 10^{-4} scc/m @ 34.5kPa
External	≤1 x 10^{-3} scc/m @ 34.5kPa (5 psi)	≤1 x 10^{-6} scc/m (all welded)
Power	≤ 10 W @ 28 Vdc, 20°C (68°F) at Pull - In	2.4W at Pull - In
Cycle life	15,000 cycles	15,000 cycles

$$F = \frac{W F^{*} T_1}{K}$$

where:
F= Thrust (N)
W= Flow Rate (Kg/s)
T_1= Inlet Gas Temperature (°K)
F^{*}= Thrust Coefficient
K= Flow Constant for Nitrogen, 0.0.3975 (s√K/m)

The reported thrust level is the aver-age of three values calculated from data measured at inlet pressures of 0.035 MPa (5 psi), 0.35 MPa (50 psi) and 0.69 MPa (100 psi).

Performance Requirements and Demonstrated Performance

Table 1 list the requirements specification and the demonstrated values from the two proof-of-concept units.

Future Thruster Development

Since this was a minimum cost and therefore a minimum limit of scope contract, not all thruster characteristics were demonstrated. Future work will include. additional life cyck testing and exposure to environmental extremes. Bawd on results from test programs with similar thrusters, we predict that the Pluto Fast Flyby thruster is capable of satisfying all program requirements.

Latch Valve

The proof-of-concept latch valve is shown in Figure 6 and is 21.3 mm (0.84 in) in diameter by 43.2 mm (1.7 in) long and weighs 73 g (0.161 lbs). A cross-section of the valve is given in Figure 7.

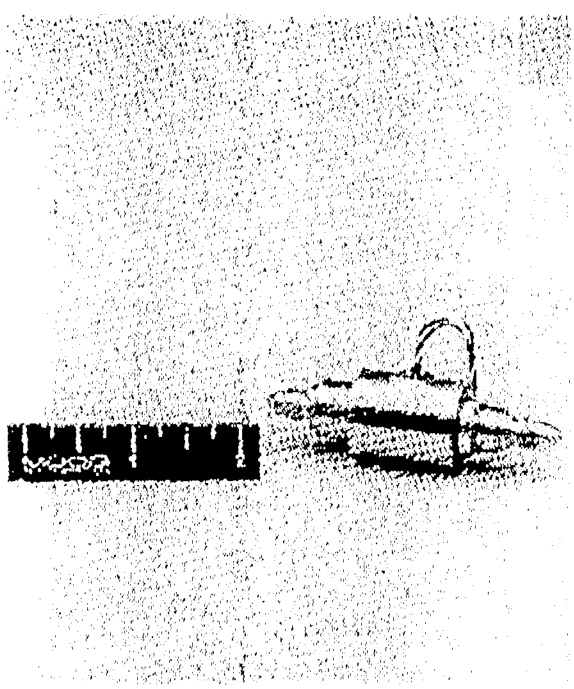

Figure 6 Proof of Concept Latch Valve

The latch valve is a coaxial solenoid with permanent magnets whkh provide bistable operation. The valve is hermetically sealed with two electron beam welds at each erect of the valve body. The solenoid coils and the permanent magnets are located outside the pressure containment portion of the valve body. Magnetic field pieces are utilized at the ends of the coils and between the permanent magnets and the valve body to efficiently transmit the magnetic flux through the thin wall portion of the body into the polepieces and the working air gaps of the solenoid. The valve body is a thin wall 302 CRES tube (titanium is an alternate material) with threaded ends to facilitate assembly and to allow the valve stroke to be set by shims. ‘A poppet assembly with a molded rubber seal is mechanically attached to the armature and is configured such that the gas can pass through the center of the poppet when the valve is open. A small 10 micron inlet filter prevents contamination from entering into the valve. The armature, polepieces, field pieces and coil cover are made from 430 CRES. The poppet, seat and inlet and outlet tubes are made from 302 CRES.

Magnetic circuit

The magnetic circuit for the latch valve is shown in Figure 8. The flux generated by radially charged neodymium magnets provide the latching force in both the open and closed positions. Since the. length of the air gaps are different at each end of the armature, the flux density and therefore the magnetic form is also unequal. The shorter air gap will always carry the greatest amount 0[flux producing the larger form. The magnetic circuit is sized to provide latching forces large enough to securely hold the armature in the last commanded position under all environmental conditions. When the coils are energized the coil generated flux will add to the permanent magnet flux at one air gap and subtract from the permanent magnet flux at the other air gap.

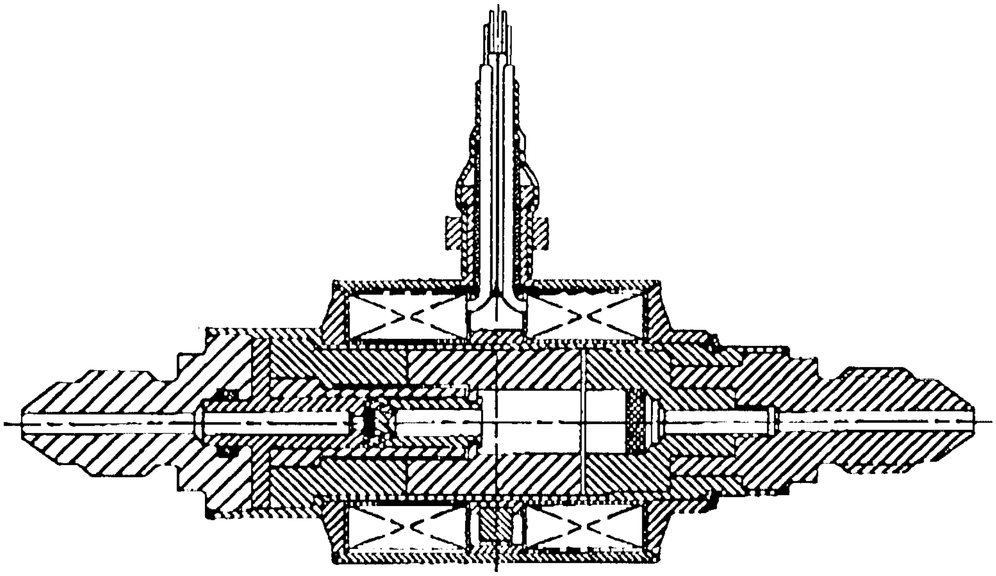

Figure 7 Latch Valve Cross Section

The result is a net force on the armature which moves the armature to the desired position. The polarity of the opening and closing coils are reversed to provide the proper armature motion. The poleface area on the "closed" end of the *armature* is aired to control the force applied to the seal. The valve is operated by applying a 50 ms pulse to either the open or close coil.

Performance Requirements and Demonstrated Performance

Table 2 lists the specification requirements and the demonstrated values from the proof-of-concept hardware

Future Latch Valve Development

In order to demonstrate that the existing latch valve

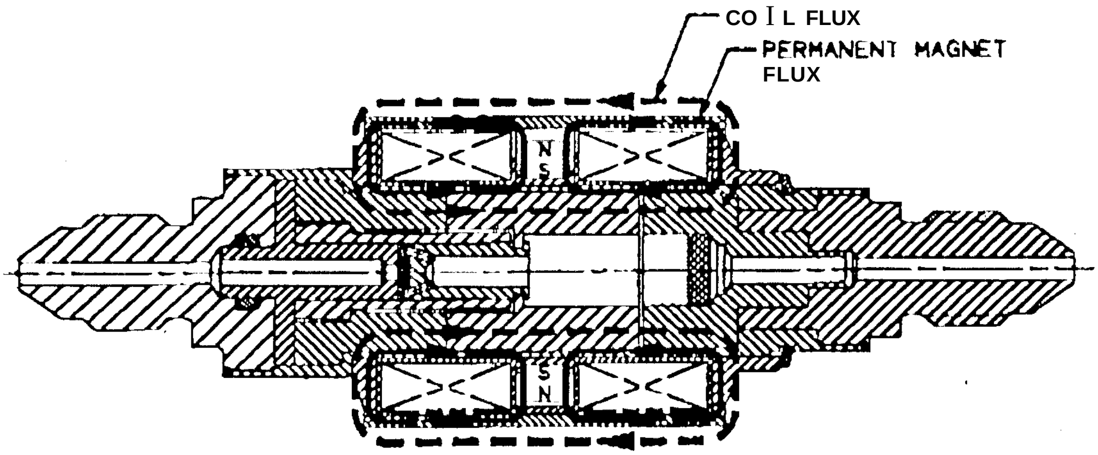

Figure 8 Latch Valve Magnetic Circuit

Table 2 Latch Valve Characteristics.

Characteristic	Requirement	Demonstrated Value
Operating Fluids	GN_2, Hydrazine Vapors	GN_2
Weight	≤ 100 g(0.22 lbs)	73 g (0.16 lbs)
Operating Pressure	2.07 MPa (300 psi)	2.07 MPa
Proof Pressure	3.1 MPa (450psi)	3.1 MPa
Burst Pressure	≥ 5.2 MPa (750 psi)	≥ 5.2 MPa
Back Pressure Relief	420± 280 kPa (6 0 ±40 psi) differential]	620 kPa (88.5 psi)
Flow Rate GN_2	2.0sl/m(122in^3/m)(max) @ s 14 kPa (2 psid)	2.0sl/m(122in^3/m) " @ 0.6 kPa (0.0S paid)
Internal Leakage	≤0.01 cm^3/m GN_2 @ 2.07 MPa (300 psi)	0.0 cm^3/m @ 2.01 MPa
External Leakage	≤1 x 10^{5} cm^3/m @ 2.07 MPa	0.0 cm^3/m
Voltage - Operating	2A to 32 Vdc	2A to 32 Vdc
Pull-In	20 Vdc	≤6Vdc open ≤ 2 Vdc close
Fewer	15W max. @28 Vdc,20°C(68°F)	13.8 W @28 Vdc,20°C
Cycle Life	≥ 5,000 cycles	50,000 cycles
Response	50ms @ 24Vdc, 2.07 MPa(300 psi), 45°C(113°F)	2ma @ 24Vdc, 2.07 MPa, 20"C
Filtration	≤ 10 micron absolute	10 micron absolute

design is flight ready additional environmental testing will have to be performed. JPL is planning to run operating and non-operating perform ance throughout the temperature range of -20°C (-4 °f) to 70°C (158°F). Also performance during and after exposure to vibration and shock will be demonstrated in the near future.

Design options for the addition of a switch for positional status indication are being evaluated. This option will increase the mass of the valve depending on the type of switch utilized. A mechanical switch will produce tbe greatest increase in mass. If a Hall Effect Device is used the mass increase will be minimized.

Regulator

The Pluto Fast Flyby regulator design was adapted from the Moog regulator developed for the ROSAT "Mixed Gas Pressurization System". The Roentgen SATellite called ROSAT is a scientific satellite funded by the German Government and designed to study x-ray emissions by mapping the x-ray activity over a two year period. It was launched in June 1990 by a Delta rocket from Cape Kennedy. ROSAT

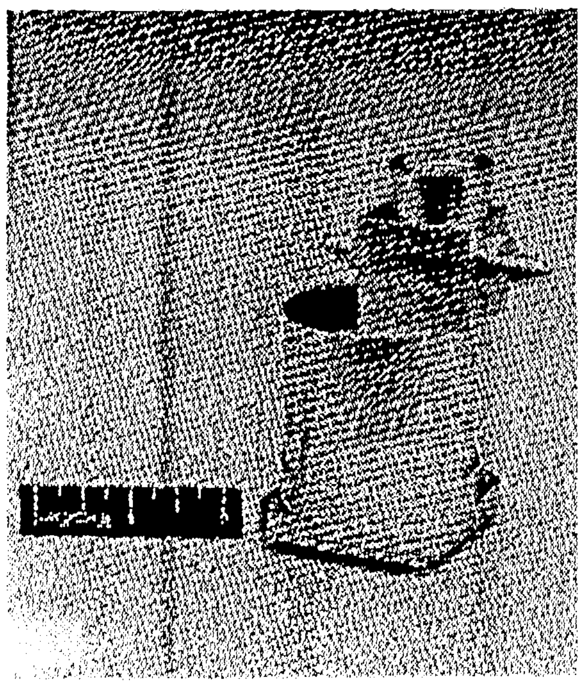

Figure 9 Proof of Concept Regulator

has exceeded it's design life of two years and is just coming to the end of it's gas supplies,

The ROSAT ***regulator*** was redesigned and repackaged to address the unique requirement of the Pluto Fast Fly-by mission; lower flow, lower outlet pressure and less mass. Figure 9 shows a photograph of the proof-of concept regulator and Figure 10 is a cross section of a flight design.

Operation

The regulator is designed to operate with a 2..07 to 0.10 MPa (300 to 15 psi) inlet supply of GN_2 while maintaining an outlet pressure of 34.5* 2.07kPa (5±0.3 psi). Once the regulator reaches 0.1MPa (1S psi) inlet pressure the regulator is full open and at the end of providing a controlled outlet pressure level. If flow demand persists, the regulator will simply stay ***open and act*** as a fixed orifice restriction with the outlet pressure dropping below 34S kPa (5 psi) until all the gas is used.

The regulator achieves this performance characteristic try seining outlet pressure and modulating a very small ball valve. When the system *k* initiated and inlet pressure appears around the ball, gas flows upward past the seat edge in the annular flow passage between the seat and the poppet stem to the outlet. If the downstream thrusters are closed the outlet pressure will rise until the hall poppet shuts off the flow. Increasing outlet pressure compresses tbe bellows and the force reference or regulation spring. The belleville spring attached to tbe lower bellows end plate serves as a lever between the poppet stem and the bellows. The pivot point is tbe outside edge of the belleville spring. The sensing bellows motion is four times larger than the valve stroke. When the outlet pressure reaches a value a little above 34.5 kPa (5 psi), the lower bellows end plate has moved enough for the ball poppet to seal against the seat not allowing any further flow or outlet pressure increase, The regulator is now closed and the outlet pressure trapped (locked up) downstream of the regulation valve.

Any flow demand on the outlet will now cause the outlet pressure to drop thus making the force balance between the spring and bellows go negative. The higher spring force moves the lower bellows end plate and poppet stem downward opening the valve and allowing flow to the outlet which again increases the outlet pressure. The increasing outlet pressure starts to close the valve. In thin manner, outlet pressure is regulated around a pressure net point of

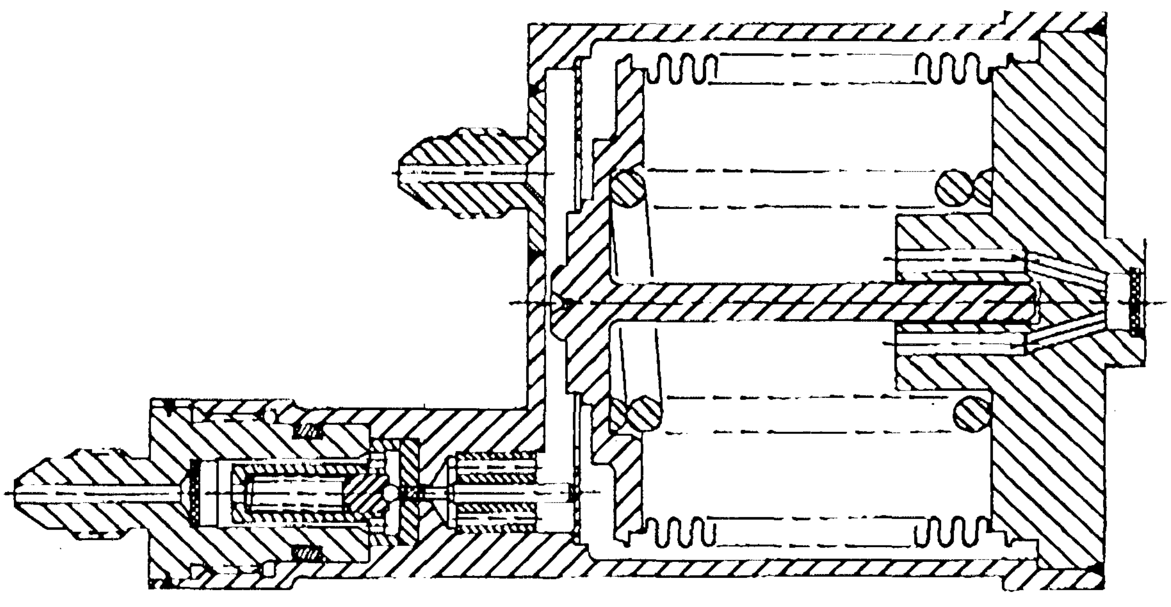

Figure 10 Flight Regulator Cross Section

34.5 kPa (S psi) **pressure differential with respect to ambient.**

Regulator Performance Characteristics

Regulator performance characteristics arc a measure of how wc]] the outlet pressure is maintained under all possible flow and inlet pressure conditions. Accuracy of controlled outlet pressure (width of pressure control band) is dependent cm the following four major parameters and their effects; droop, inlet pressure range, operating temperature range and friction. A portion of the allowable pressure control band needs to be allocated to each of these parameters.

Droop

Regulation droop or the drop in outlet pressure which is required to open a regulator from zero to full floc. It is a part of any regulator design. Tbe amount of droop is a judicial design choice influenced by the regulation spring rate and the poppet seat configuration. A value of 1.04 kPa (0.01S psi) was allocated to droop. **This translates into a force change of 0.0S8 N (0.26 lbf) out of 44.48 N (10 lbf) to go from the closed position to the full open stroke** when the inlet pressure is a minimum.

Inlet Pressure Range

Minimum inlet pressure and maximum flow requirements sizes a regulator, A flow rate of 2sl/m GN_2 at 0.345 MPs ((50 psi) upstream pressure and 34.S kPa (5 psi) downstream pressure is met with an equivalent square edge orifice diameter of approximately 0.356 mm (0,014 in) diameter. The Pluto Fast Flyby regulator was designed to this maximum flow area with a scat diameter of 13 mm (0.051 in). For simplicity and compactness an inlet pressure unbalanced design was selected and therefore allowances for the range of inlet pressures **must be made. The** high inlet pressure Of 2.07 MPa (300 psi) exerts a higher force on the ball poppet than when the inlet pressure is at 0.345 MPa (SO psi), This difference will result in a shift of the nominal pressure set point. This is part of the pressure band and calculates to be 5.52 kPa (0.08 psi) for the 1.73 MPa (250 psi) inlet pressure range.

Operating Temperature Range

Ambient operational temperature range from -20°C (-4°F) to 70"C (158°F) will result in a small but measurable modulus change in the spring material. By our estimates, this is about 3% of the 44.48 N (10 lbf) spring and bellows form and hence. a delta force of 0.067 N (0.015 lbf) which translates into a regulation pressure shift of approximately 1.06 kPa (0.15 psi).

Friction

Contact friction between the pressure sensing parts in the regulator is another contributor to outlet pressure variation. By selecting a design with a bellows and belleville spring, friction was held within specification tolerances.

Regulation accuracy bandwidth is the sum of the effects of droop, inlet pressure range, temperature range and friction as shown below:

Parameter	Delta Pressure ---1
hoop	-0.117 kPa (0.015 psi)
Inlet Pressure	±0.552 kPa (0.08 psi)
Temperature	±1.035 kPa (0.15 psi)
Friction	±0.690 kPa 0.10 psi)
Total Accuracy	±3.312 kPa 0.48 psi)

During all development testing at Moog the regulator demon..trated a pressure regulation accuracy of 3.45 kPa (0.50 psi) under all combinations of operating conditions which is well within the required band of 4.14 KPa (0.6 psi). A typical regulator output flow - pressure curve is shown in Figure 11.

Extensive development testing was performed to verify regulator performance in the' • ca6 of leakage, lockup pressure, overshoot and slam start operation over the temperature range of -20°C (-4°F) to 70°C (158°F). In all cases the regulator was well within specification requirements. Table 3 summarizes the specification requirements and the demonstrated performance of the proof-of-concept hardware.

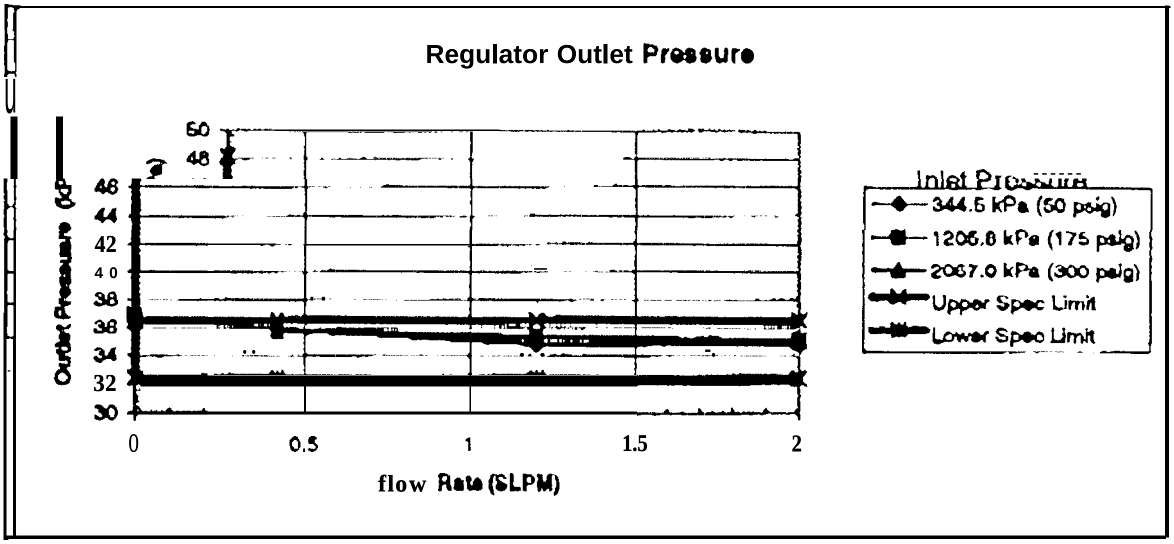

Figure 11 Regulator Outlet Flow

Future Regulator Development

The regulator was exposed to more development testing than either the cold gas thruster or the latch valve, As a result the design is mature enough that it is ready for a formal qualification test program.

Summary and Conclusions

Three miniature components for the Pluto Fast Flyby propulsion system have been successfully demonstrated with proof-of-concept hardware and initial development testing. This development teat program demonstrates the feasibility of extremely

Table 3. Regulator Characteristics

Characteristic	Requirement	Demonstrated Value
Operating Fluids	GN_2, Hydrazine Vapors	GN_2
Weight	≤0.3 kg (0.136 lbs)	0.294 kg Predicted flight weight
		0.5 kg proof-of-concept weight
Operating Pressure	2.07 to 0.345 MPa (300 to 50 psi)	2.07 to 0.345 MPa (300 to 50 psi)
Proof Pressure (inlet)	3.2 MPa (450 psi)	3.2 MPa
Proof Pressure (outlet)	2.07 MPa (250 psi)	2.07 MPa
Burst Pressure (inlet)	≥ 5.2 MPa (750 psi)	≥ 5.2 MPa (analysis)
Burst Pressure (outlet)	≥ 3.5 MPa (500 psi)	≥ 3.5 MPa (analysis)
Outlet Pressure	34.5±2.07 kPa (5 ±0.3 psi) @1.0sl/m (61.02 in^3/m)	34.5±1.73 kPa@1.0sl/m
Lockup Pressure (max.)	48.3 kPa (7 psi)	41.4 kPa (6 psi)
Flowrate	2.0 sl/m (122 in^3/m) @ 34.5 kPa (5 psi)	2.0 sl/m @ 34.5 kPa
Internal Leakage	≤ 0.01 cm^3/m GN_2 @2.07 MPa (300 psi)	≤ 0.01 scc/m GN_2 @2.07 MPa
External Leakage	≤ 1 x 10^{-5} cm^3/m GN_2	≤ 1 x 10^{-5} cm^3/m GN_2
Temperature	-4°C (-20°F) to 70°C (158°F)	-4°C to 70°C
Overshoot @ Slam Start	42 kPa (6.08 psi) max. pressure	< 42 kPa

light weight propulsion components and provides the confidence to continue the advance planning for a lightweight spacecraft for the Pluto mission.

Acknowledgment

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